Efficient high-power Tm:YAG laser at 2 μm, end-pumped by a diode bar

C. Bollig 1, W.A. Clarkson, R.A. Hayward *, D.C. Hanna

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

Received 15 April 1998; accepted 2 June 1998

Abstract

Efficient, room-temperature operation of a Tm:YAG laser, end-pumped by the re-shaped output beam from a 20 W diode bar, is reported. At a rod mount temperature of 20°C and with 13.5 W of diode pump power incident on the Tm:YAG rod we obtained 4.1 W of output at 2.013 μm in a near-diffraction-limited beam with corresponding $M^2$ values in orthogonal planes of 1.4 and 1.2. The prospects for further power-scaling are discussed. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

Diode-pumped Tm-doped solid-state lasers operating in the eye-safe 2 μm spectral region have received growing interest over recent years [1,2], due to their numerous applications in important areas such as medicine, laser radar and remote sensing. For many of these applications, the requirement for high average powers has restricted the scope for choice in laser material to crystals, such as Tm:YAG, which have good thermo-mechanical properties and hence a high fracture limit. In common with many other Tm-doped crystals, Tm:YAG has the attraction of a quantum efficiency of ~ 2, when it is doped with sufficiently high concentrations of Tm$^{3+}$ (typically at least ~ 3% at.), due to efficient cross-relaxation with neighbouring Tm$^{3+}$ ions, which results in two excited Tm$^{3+}$ ions for each absorbed pump photon [3]. This leads to the prospect of very high lasing efficiencies (comparable to those achievable in diode-pumped Nd:YAG lasers), and also implies significantly reduced thermal loading (compared to the situation without cross-relaxation), which is vitally important for high-power operation. In addition, Tm:YAG also benefits from a long fluorescence lifetime $t_f$ ~ 11 ms [4], which is attractive for high-energy Q-switched operation. Unfortunately, due to the quasi-three-level nature and relatively low value for $\sigma t$ in Tm:YAG (~ 3 times smaller than for 1.064 μm transition in Nd:YAG), scaling efficient end-pumped lasers to high average powers, whilst maintaining good beam quality, has proved very difficult. The main problem is the poor beam quality with highly elongated shape, provided by commercially available high-power diode bars, which renders them difficult to focus to the intense circular beams required for efficient end-pumping of low gain quasi-three-level lasers. To lessen the demands placed on pump beam quality, it has been standard practice to cool the Tm:YAG rod to reduce the re-absorption loss [1,5,6], in some cases to temperatures as low as ~ 40°C. This has allowed limited power-scaling using polarisation-coupled broad-area diode-laser pump sources, but at the expense of significant added complexity.

In this Letter we report efficient, multiwatt operation of a Tm:YAG laser at room temperature by longitudinally pumping with the re-shaped output of a single 20 W diode bar. The pumping scheme, a very important element in this work, is similar to the arrangement described in Ref. [7], incorporating a two-mirror beam shaper to re-configure the output from a conventional 20 W cw diode bar. The
two-mirror beam shaper allows the highly elliptical diode-bar output beam with beam quality factors; $M_x^2 \approx 2000$ (parallel to the plane of the array) and $M_y^2 \approx 1$ (in the orthogonal plane) to be re-formatted with nearly equal beam quality factors in orthogonal planes without significantly reducing the brightness. In an optimised arrangement and depending on the initial beam quality factors, $M_x^2$ and $M_y^2$ for the diode bar, it is possible to achieve, after re-shaping, values for $M_x^2$ and $M_y^2$ as low as 40–50, with the range 60–100 being more typical. This diode-bar end-pumping configuration has already been successfully applied to low-gain transitions at 946 nm [8] and 1123 nm [9] in Nd:YAG yielding multiwatt laser performance. The same basic strategy has been adopted for achieving efficient, multiwatt operation of Tm:YAG at $\sim 2 \mu m$.

2. Experiment

The pumping scheme, shown in Fig. 1, is similar to that described in Ref. [7], but with the 20 W diode bar (Opto Power Corporation OPC-AO20-mm-CS) selected for temperature tuning to the absorption peak at 785 nm in Tm:YAG. The re-shaped output beam emerging from the two-mirror beam shaper was focussed with an arrangement of crossed cylindrical lenses of focal lengths: two 50 mm for the plane ($x-z$) parallel to the array, and 75 mm for the orthogonal ($y-z$) plane. The resulting focussed beam was nearly circular in cross-section with beam radii ($1/e^2$ intensity radius), 172 $\mu m$ $W_x$ and 179 $\mu m$ $W_y$, and beam quality factors, $M_x^2 = 99$ and $M_y^2 = 97$, in the $x-z$ and $y-z$ planes, respectively. The maximum pump power available at the focus was 15 W. With this choice of focussed pump beam size the confocal distance ($2 = \pi W^2 f / M^2 \lambda_0$, where $n$ is the refractive index) inside the Tm:YAG, calculated to be $\sim 4.5$ mm, was more than twice the effective pump absorption length of $\sim 2$ mm for the pump, thereby ensuring a good spatial overlap with the laser mode and a low threshold. The Tm:YAG resonator design employed, shown in Fig. 2, was a simple two-mirror cavity consisting of a convex input mirror with high reflectivity (> 99.8%) at the lasing wavelength (2.013 $\mu m$) and high transmission (> 90%) at the diode pump wavelength, a Tm:YAG rod with both end faces antireflection coated at the lasing wavelength and coated for high transmission (> 93%) at the pump wavelength. The concave output coupler had a transmission of $\sim 3\%$ at the lasing wavelength and a radius of curvature of 50 mm. The 7(at.\%) doping level in the 8 mm long Tm:YAG rod was sufficient to promote efficient cross-relaxation and ensure that a large fraction (> 98\%) of the pump was absorbed. To allow efficient heat removal the laser rod was mounted in a water-cooled copper heat-sink maintained at a temperature of 20°C and positioned $\sim 5.5$ mm from the pump input mirror. The radius of curvature of the convex input mirror was selected as $\sim 150$ mm to provide partial compensation of the thermal lens in the laser rod, which was estimated to have a focal length of 48 mm at the maximum available pump power [10]. Both curved mirrors were mounted on translation stages to allow fine adjustment of their positions with respect to the Tm:YAG rod, this being necessary to achieve the appropriate mode-matching condition for optimum beam quality. With this arrangement, and using a total cavity length of approximately 32 mm, the resonator was stable over the entire range of pump power, with the TEM$_{00}$ beam radius in the Tm:YAG rod calculated to be $127 \mu m$ at very low pump powers (< 1 W), increasing slightly with increasing pump power to 130 $\mu m$ at the maximum pump power. The TEM$_{00}$ beam size was deliberately chosen to be smaller than the pump beam size in order to minimise the beam distortion and diffraction loss due to the highly aberrated nature of the thermal lens in end-pumped lasers [10]. For a four-level laser this leads to the problem of unused gain in the wings of the pumped region which may be accessed by higher-order transverse modes thus leading to multimode operation. To avoid this problem it is usually necessary in a four-level laser to adopt further measures (e.g. using an aperture or a special resonator design [10]) to suppress oscillation on higher-order transverse modes. However, in Tm:YAG this gain is to a large extent offset by the re-absorption loss due to the quasi-three-level nature of the laser transition. This loss is especially pronounced in the wings of the pumped region, hence it helps to suppress higher-order transverse modes without the need of apertures, or special resonator designs.
3. Results and discussion

Using this resonator design and with the maximum available pump power of 13.5 W incident on the Tm:YAG laser, we have achieved 4.1 W of output at 2.013 μm in a near-diffraction-limited beam, with $M^2$ beam propagation factors in orthogonal planes, measured using a Merchantek beam profiler, of 1.37 and 1.17. The small difference in the $M^2$ values for orthogonal planes is thought to be due in part to the slightly astigmatic thermal lensing, itself a consequence of the small mismatch in the pump beam sizes in orthogonal planes. From Fig. 3 it can be seen that the laser output power is essentially linear with respect to incident pump power up to the highest power level with a slope of $\sim 34\%$. Thus for the laser configuration used in our experiments, the maximum 2 μm power appears to be limited mainly by the available pump power rather than by thermal effects. This suggests that there may be considerable scope for further power-scaling by simply increasing the pump power, e.g. by improving the transmission of the pump optics or using multiple diode bars (e.g. by polarisation coupling the output from two bars). The relatively low threshold pump power of $\sim 1.2$ W for room temperature operation (Fig. 3), compared to the available pump power, is an essential feature of the laser design for efficient operation of quasi-three-level lasers. This was made possible in these experiments by the two-mirror beam-shaping technique which allowed focussing of the pump beam to a small size. Another attraction of this intense end-pumping scheme for quasi-three-level lasers is that the laser performance is not strongly affected by the operating temperature, in contrast to the situation in many quasi-three-level laser configurations [5]. In fact, lowering the temperature of the heat-sink, and hence the rod temperature, by 10 K produced no measurable change in the maximum laser output power.

The low threshold for this laser might, at first sight, appear to suggest that further improvement in the laser output power, and hence efficiency, could be achieved using the same cavity design but with an output coupler of higher transmission ($\sim 6\%$ say) at 2.0 μm. However, under these operating conditions, the maximum output power ($\sim 2.5$ W at room temperature) was significantly lower than with the 3% transmitting output coupler. This behaviour is thought to be the result of higher upconversion losses [5], and hence greater thermal loading, associated with the higher inversion densities required for operation with the 6% transmitting output coupler, and exacerbated by the high Tm$^{3+}$ concentration. Thus one strategy to aid further power-scaling would be to reduce the upconversion loss by using a YAG rod with lower Tm$^{3+}$ concentration. The lower limit on the Tm$^{3+}$ concentration ($\sim 3\%$ at.) would be determined by the requirement for efficient cross-relaxation. This approach would, however, place yet more stringent demands on the pump beam quality since it would be necessary to use a longer Tm:YAG rod to ensure that a sufficiently high fraction of the pump is absorbed. Thus, while the results reported here indicate the benefit conferred by improved pump beam parameters, it is also clear that further benefits are still to be gained by further pump beam improvements.

4. Conclusion

In conclusion, we have demonstrated efficient room-temperature operation of a Tm:YAG laser end-pumped by the re-shaped output from a diode bar. For 13.5 W of incident pump power at 785 nm, we obtained $\sim 4.1$ W of output at 2.013 μm in a near-diffraction-limited beam with $M^2$ values in orthogonal planes of 1.2 and 1.4. This compact source should find applications in a number of areas e.g. laser radar which require a multiwatt laser operating in the eye-safe spectral region.

Acknowledgements

This work was funded by the Engineering and Physical Sciences Research Council, and R.A.H would also like to acknowledge the support of D.E.R.A. Portsdown West in the form of a C.A.S.E. studentship.

References


